

Seismic Failure of Spillway Radial (Tainter) Gates

Best Practices in Dam and Levee Safety Risk Analysis

Part G

Chapter G-3

June 2017



US Army Corps
of Engineers®



Seismic Failure of Spillway Radial (Tainter) Gates

OBJECTIVES:

- Understand failure mechanism for Tainter gates subjected to seismic loading
- Learn analysis procedures for evaluating a seismic failure of Tainter gates
- Understanding the key considerations for estimating risks for this potential failure mode.

Seismic Failure of Spillway Radial (Tainter) Gates

OUTLINE:

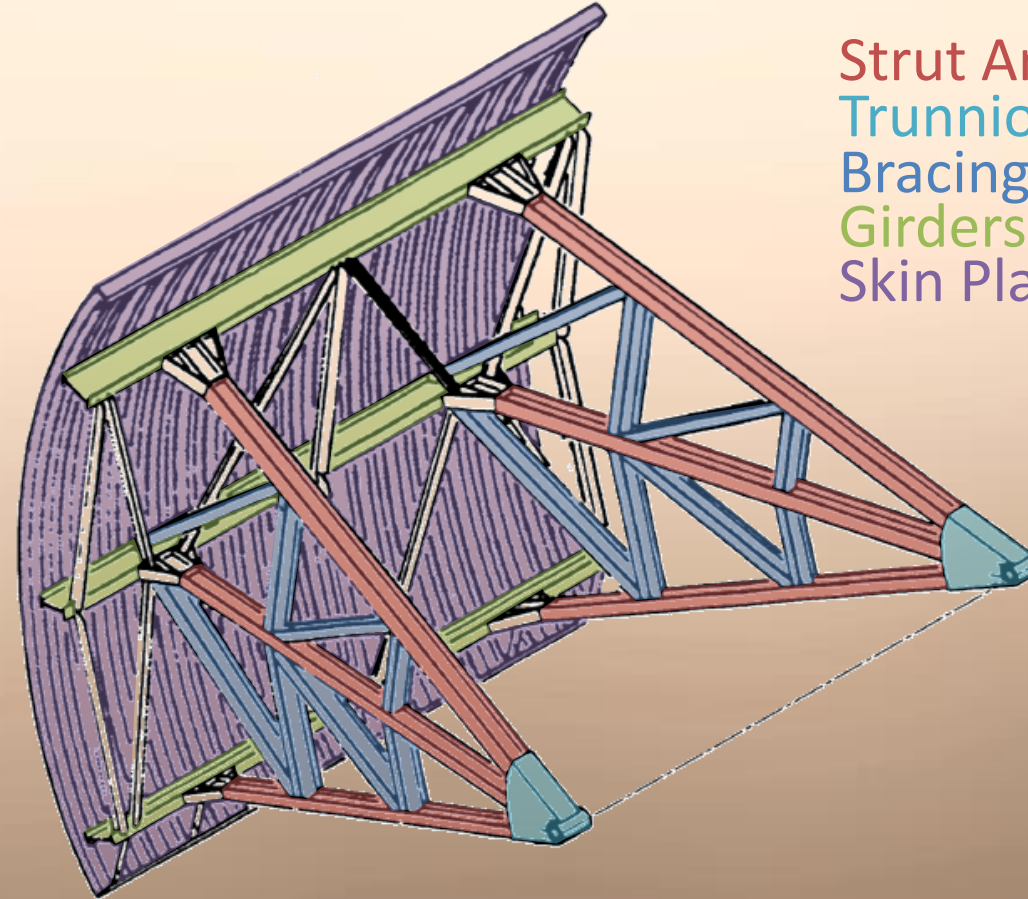
- Event Tree - Description of failure mode
- Loading
- Load Effects
- Capacity
- Probability of Failure
- Additional Failure Mode Considerations

Seismic Failure of Spillway Radial (Tainter) Gates

SUMMARY OF KEY CONCEPTS:

- There have been no recorded instances of this failure mode anywhere in the world.
- On many flood risk reduction dams, spillway tainter gates are rarely hydraulically loaded. Load combinations where two low probability events occur simultaneously must therefore be carefully considered.
- On navigation dams, spillway tainter gates experience their greatest hydraulic loads a majority of the time. It is reasonable to assume earthquake loading will happen during maximum hydraulic loading.
- Water storage and hydropower dams may have wide variation in pool elevation throughout the year, with the maximum pool usually present for only a fraction of the year.
- Since gate arms are loaded in compression, buckling is the failure mode of concern, which can be a sudden failure.

Nomenclature



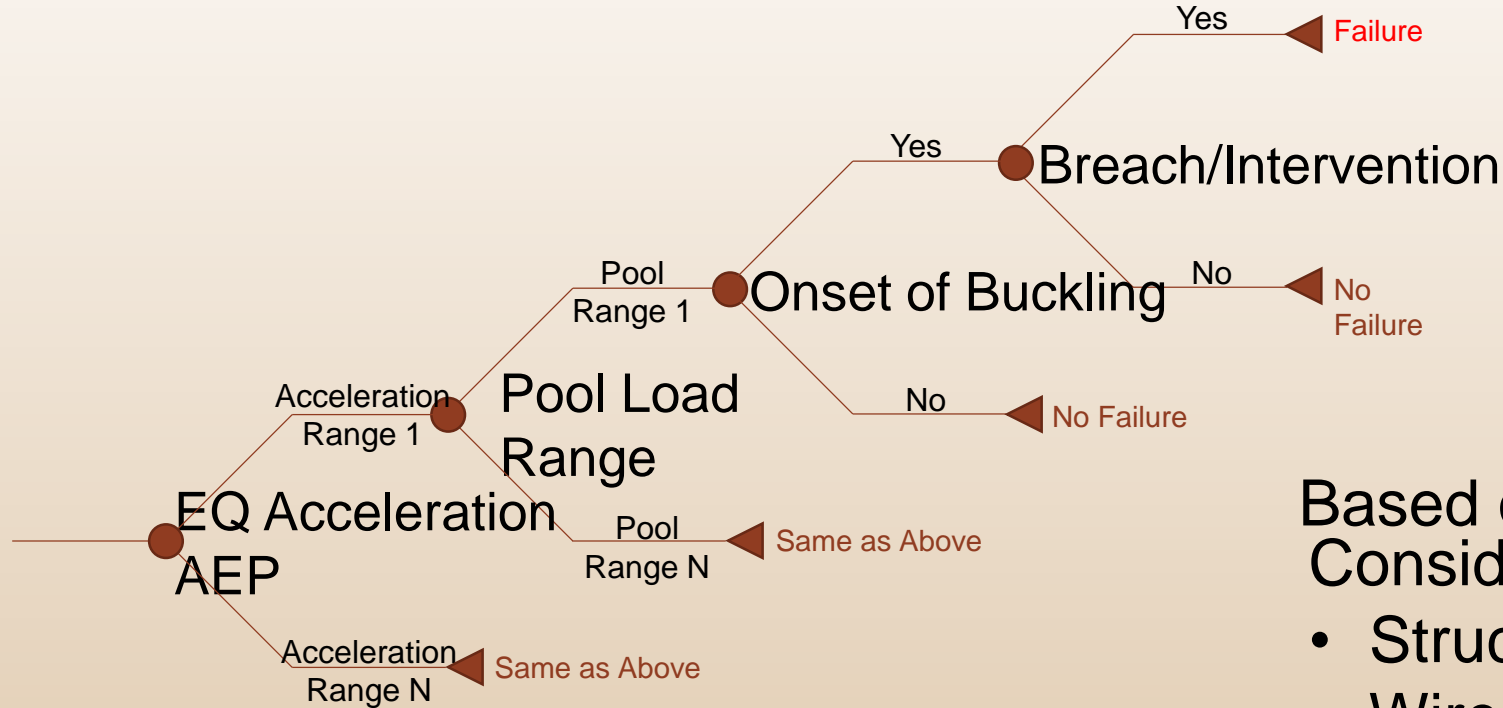
Strut Arms
Trunnion Hub and Assembly
Bracing
Girders
Skin Plate and Ribs

Spillway Gate Member Failure Mechanisms

- Yielding (Inelastic Buckling)
- Buckling
- Fatigue



Failure Mode Event Tree



Based on elicitation
Consider:

- Structure redundancy
- Wire ropes
- Trunnion ties
- Emergency closure bulkheads (may need intervention branch)

Based on
analysis and
elicitation

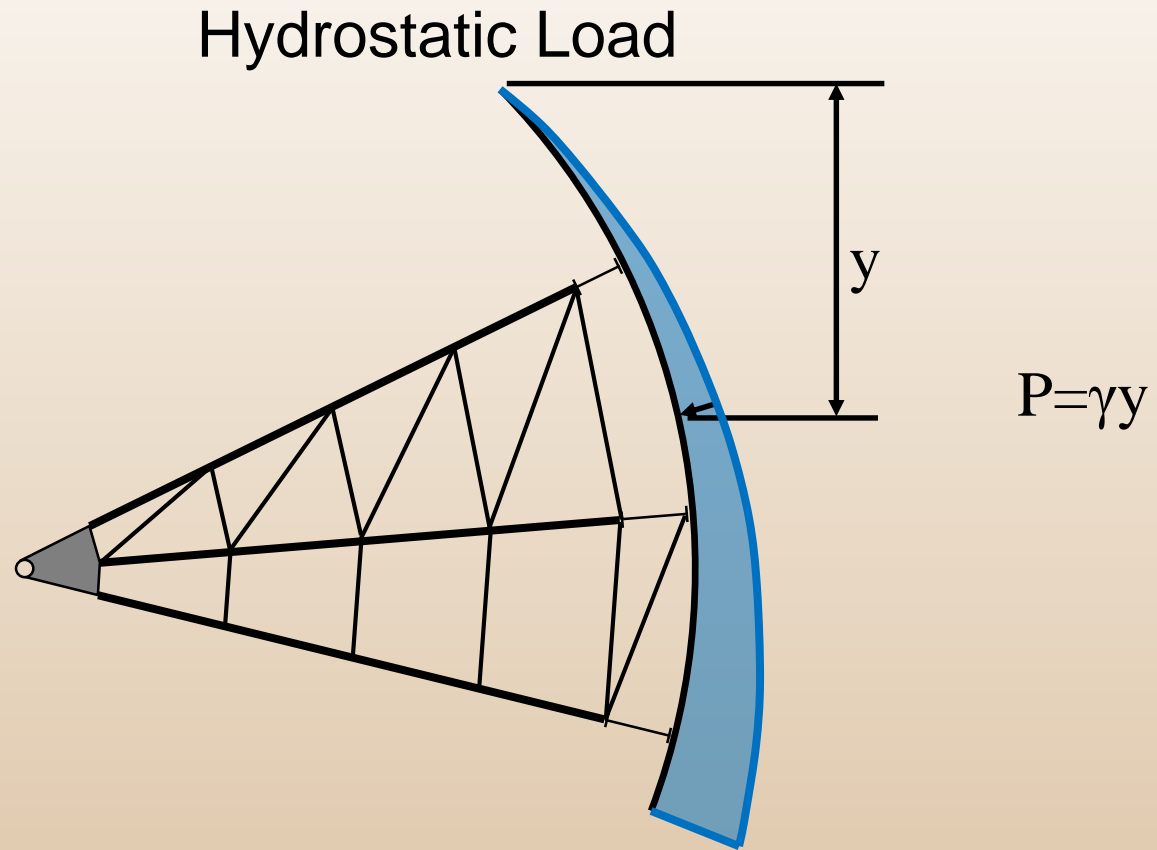


Loading

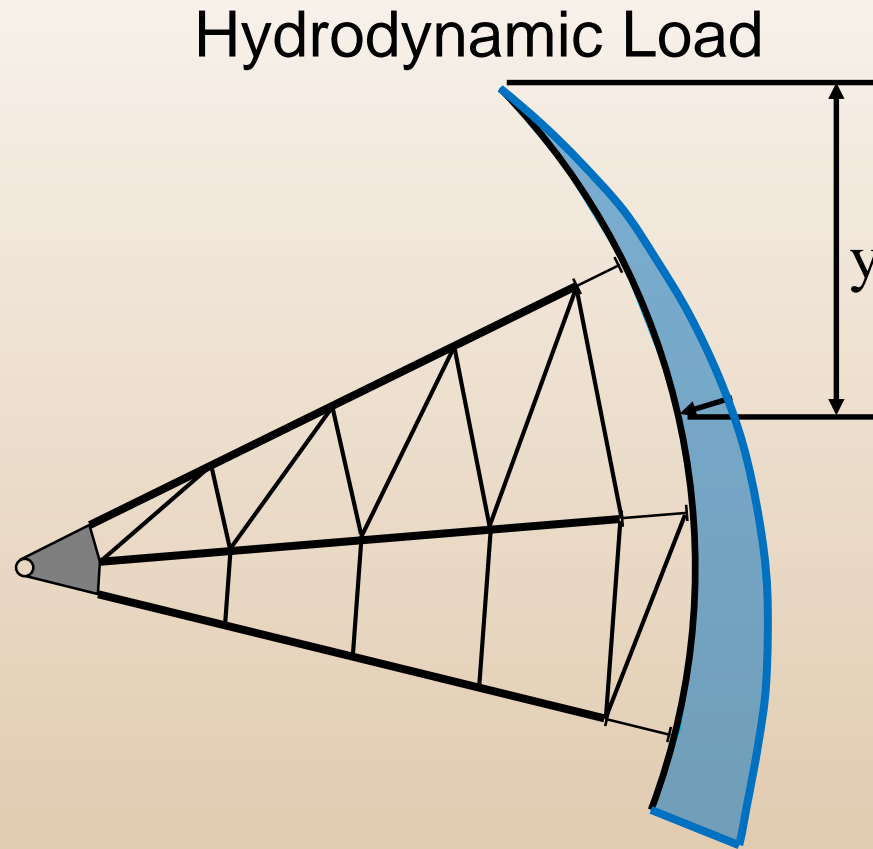
- Simplified methods are generally pseudostatic
 - Gate inertia
 - Hydrodynamic
 - Hydrostatic
- Loading must be corrected for other dynamic effects
 - Duration of loading
 - Amplification



Loading



Loading



$$p = \frac{8a_g\gamma H}{\pi^2} \operatorname{Re} \left[\left(\cos \left(\frac{2\pi t}{T} \right) + i \sin \left(\frac{2\pi t}{T} \right) \right) \sum_{n=0}^{\infty} \frac{1}{c_n(2n+1)^2} \sin \left(\frac{(2n+1)\pi y}{2H} \right) \right] \left[\left(1 - \sqrt{\frac{h}{H}} \right) e^{\frac{-1.4dy}{h^2}} + \sqrt{\frac{h}{H}} \right]$$

Loading

Hydrodynamic Load

$$p = \frac{8a_g \gamma H}{\pi^2} \operatorname{Re} \left[\left(\cos \left(\frac{2\pi t}{T} \right) + i \sin \left(\frac{2\pi t}{T} \right) \right) \sum_{n=0}^{\infty} \frac{1}{c_n (2n+1)^2} \sin \left(\frac{(2n+1)\pi y}{2H} \right) \right] \left[\left(1 - \sqrt{\frac{h}{H}} \right) e^{\frac{-1.4dy}{h^2}} + \sqrt{\frac{h}{H}} \right]$$

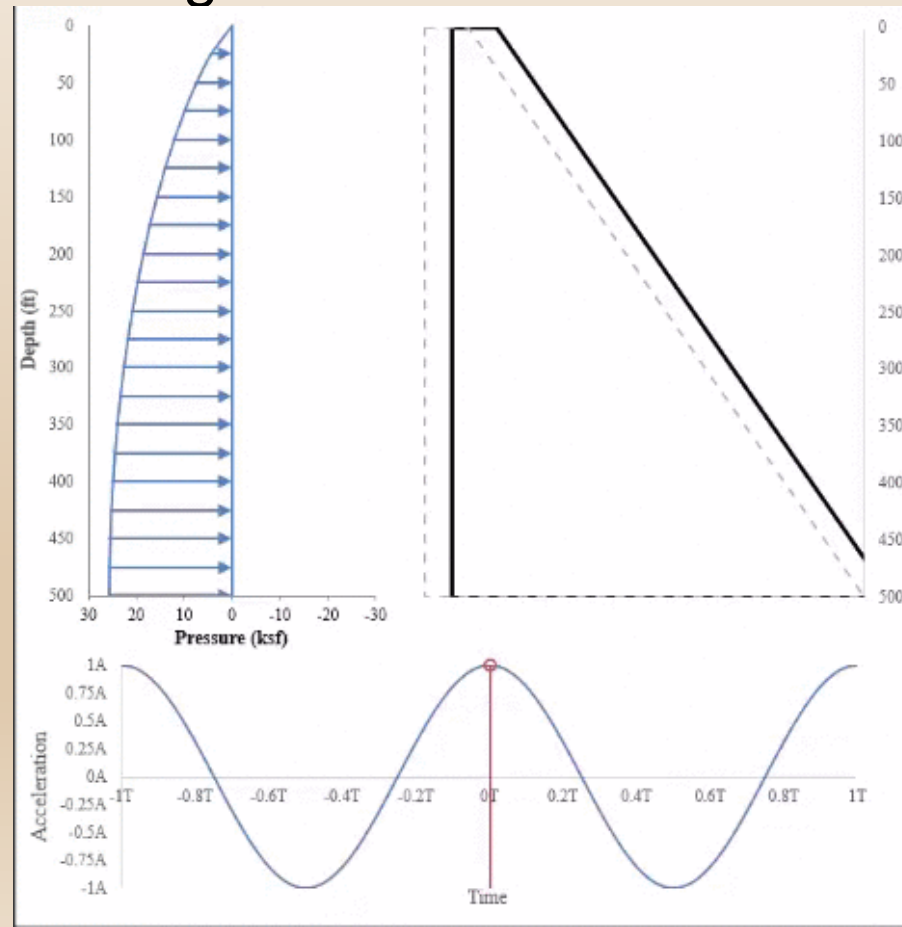
Westergaard Exact Solution

Gate Inset Correction

H=Water Depth

h=Water Depth on Gate

d=Gate Inset



Must include amplification factor and pseudo static correction



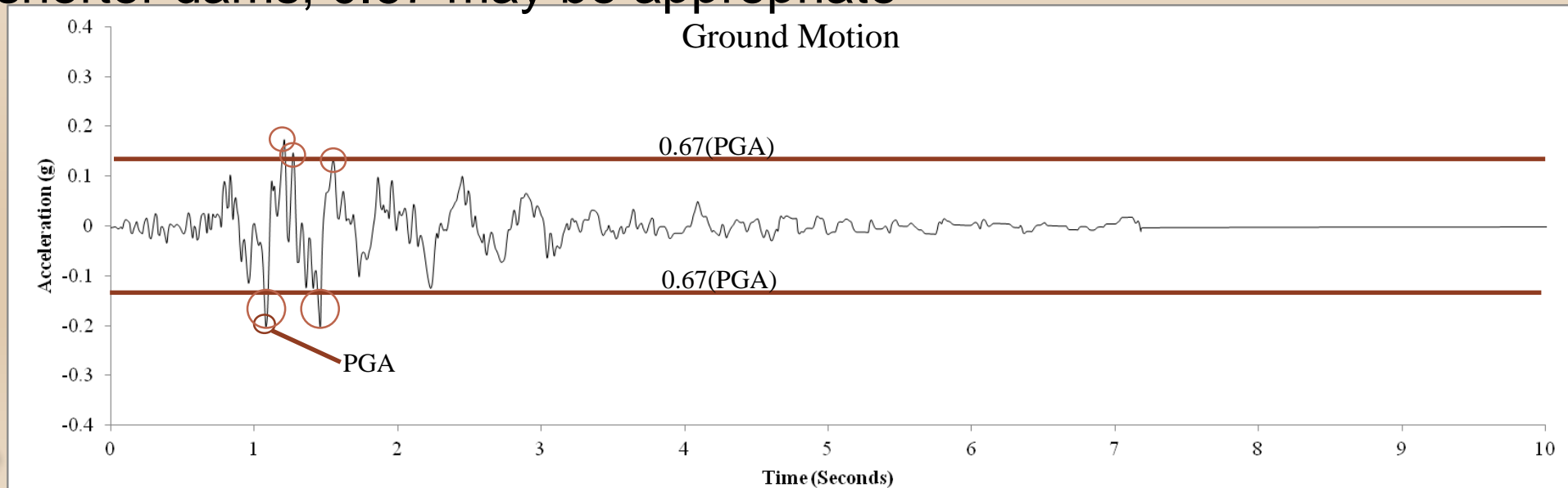
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Pseudostatic Correction:

- Accounts for the fact that the peak acceleration only occurs at one instance.
- Stability Analyses generally uses 0.67 (e.g. EM 1110-2-2100)
- Higher values up to 0.85 may be needed to account for the structural response of tall dams.
- For shorter dams, 0.67 may be appropriate



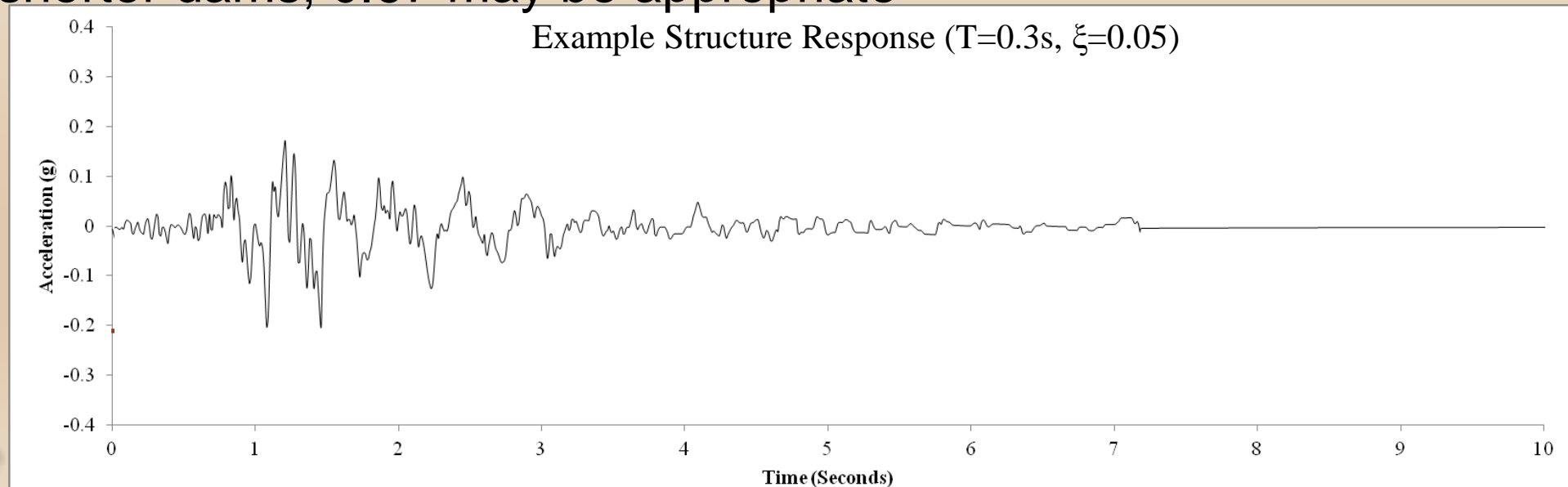
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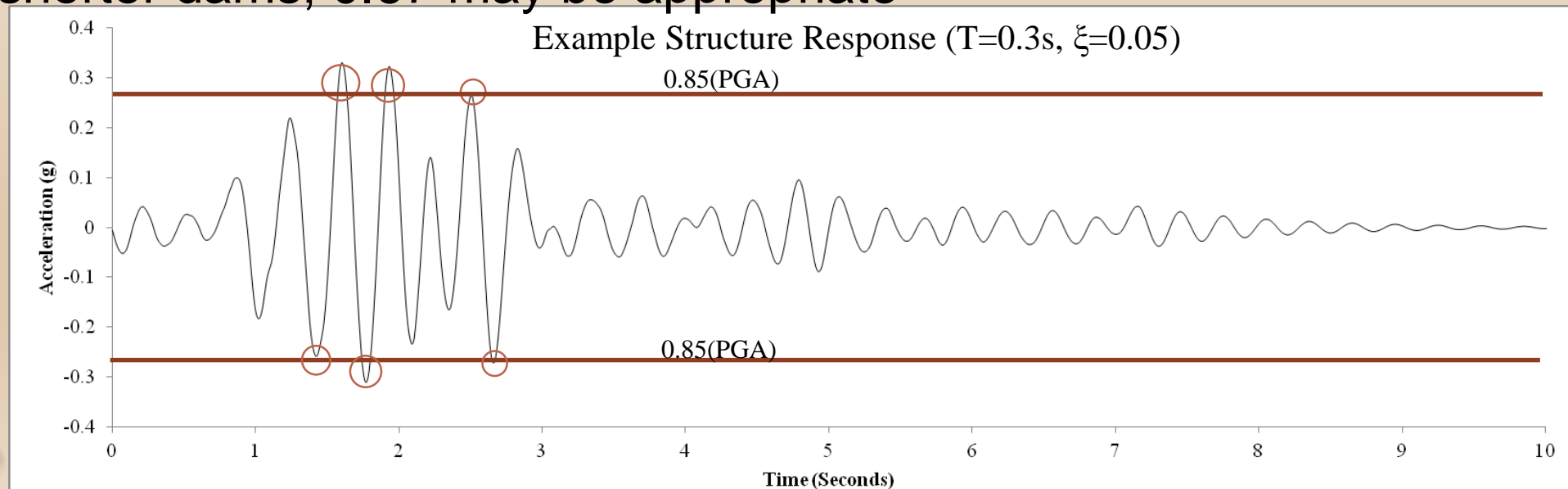
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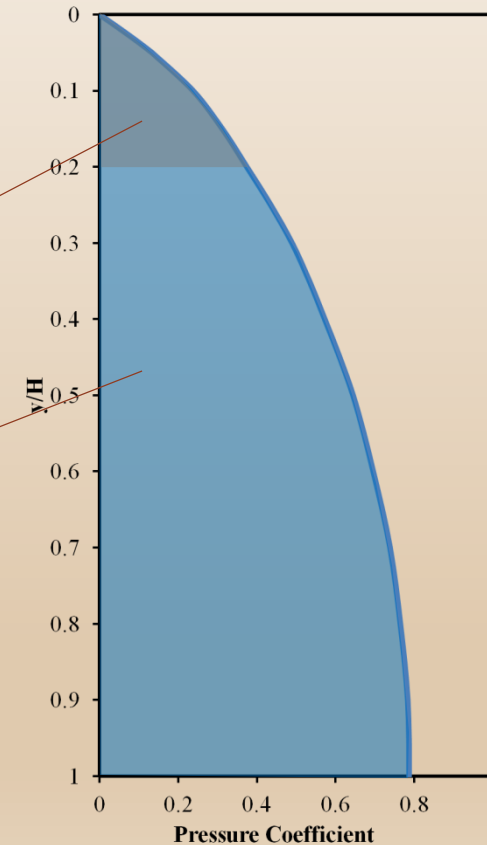
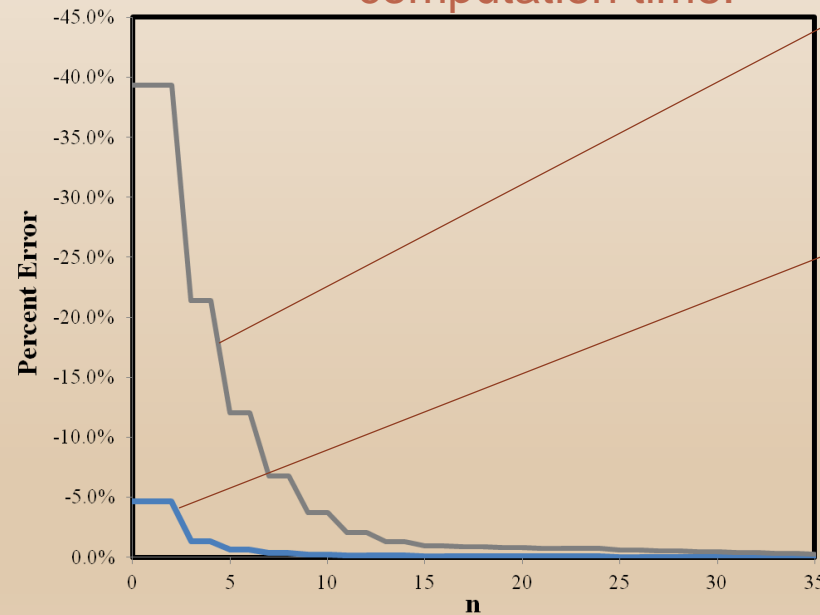


Loading

Hydrodynamic Load

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High enough for desired accuracy, low enough for computation time.

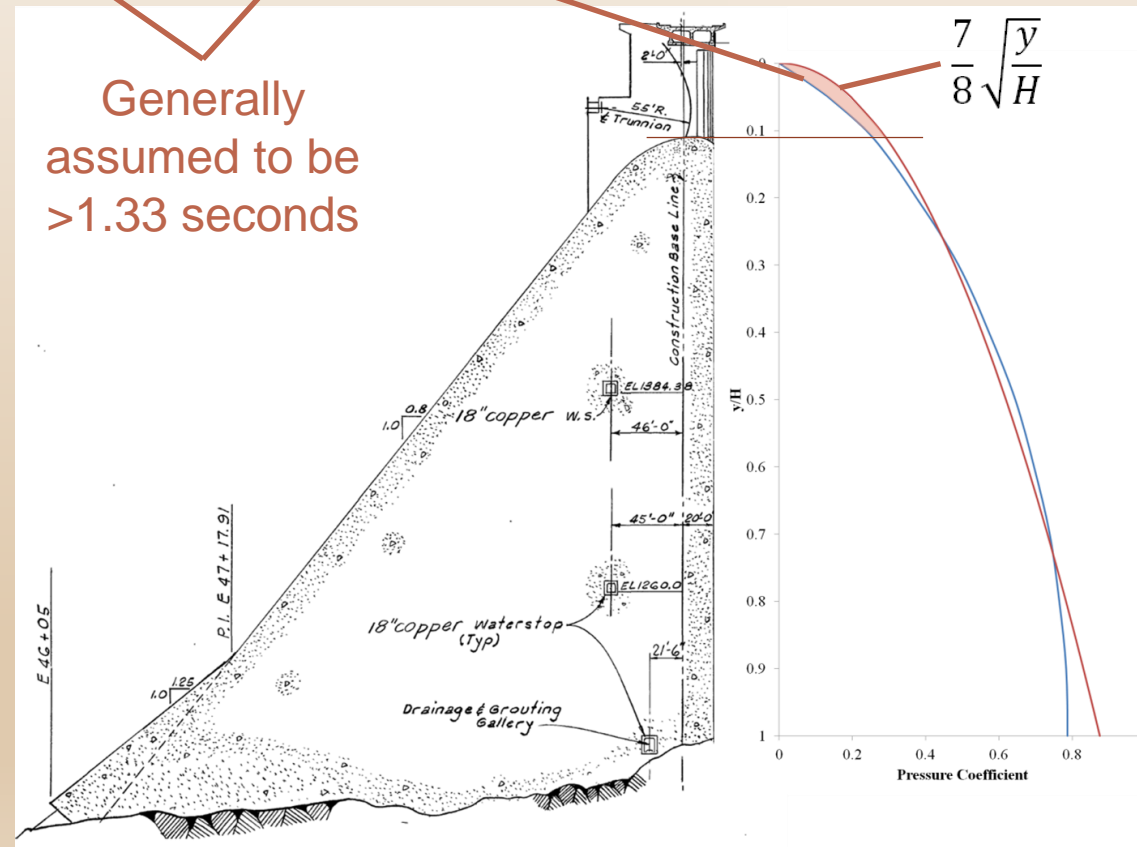


Loading

Hydrodynamic Load

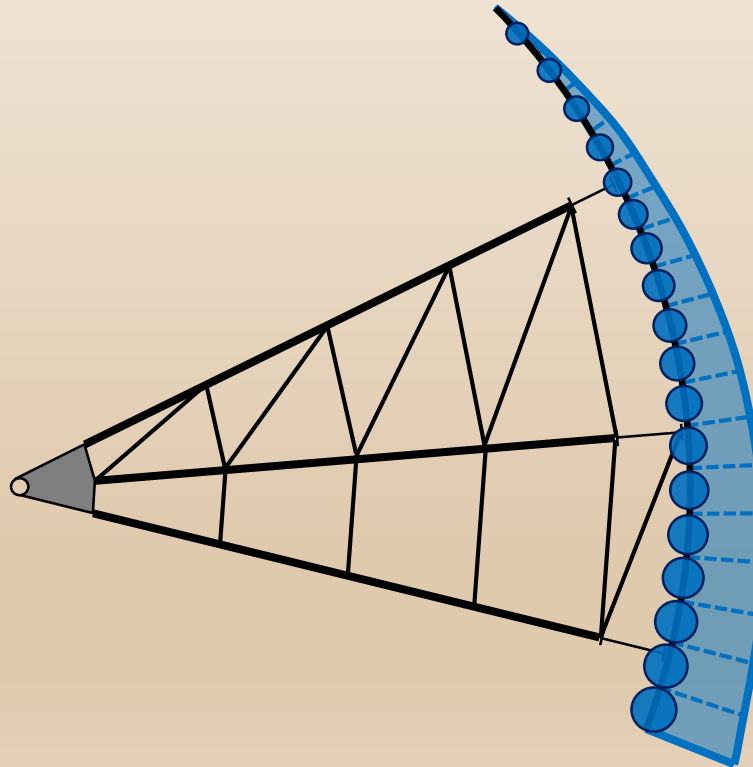
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Generally
assumed to be
>1.33 seconds



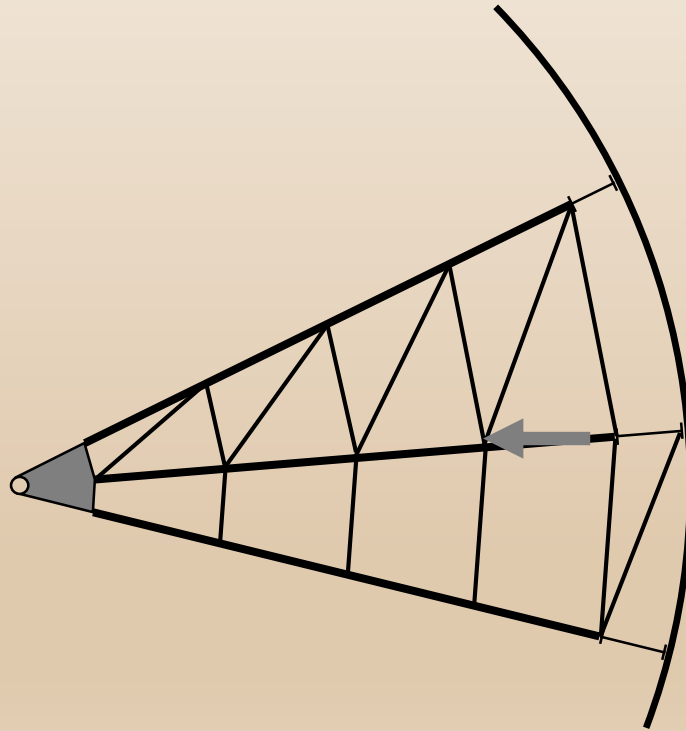
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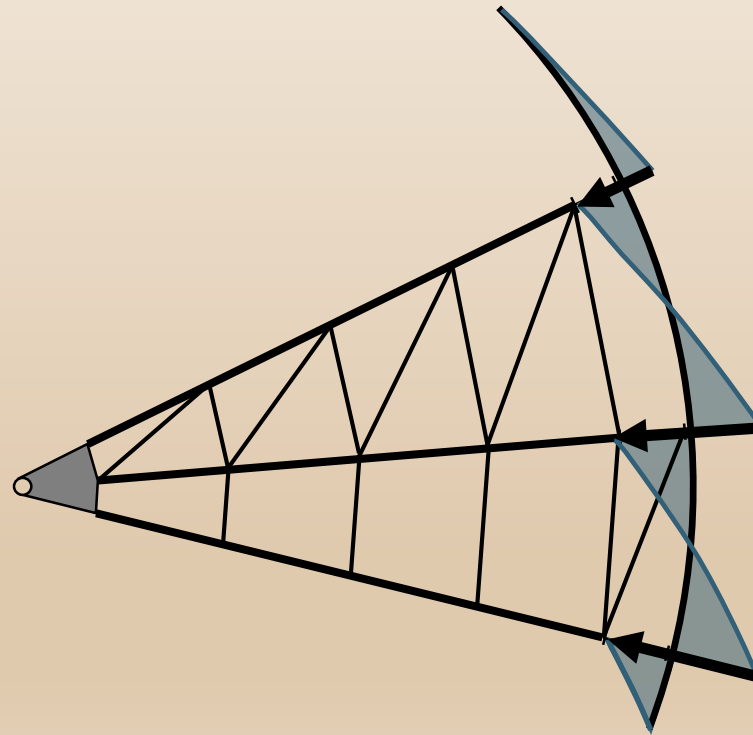
Loading

Gate Inertial Load



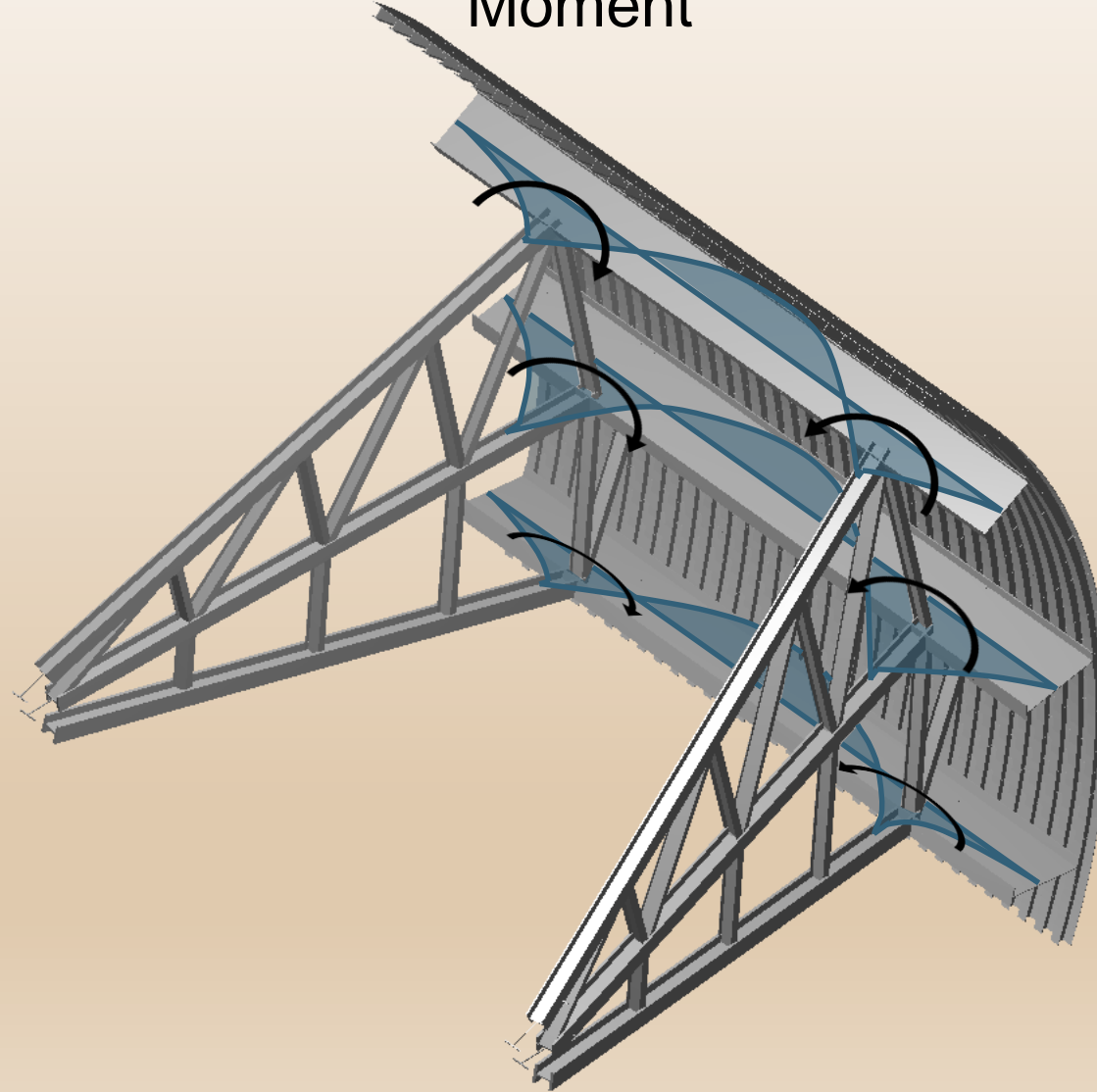
Load Effects

Strut Axial Loads



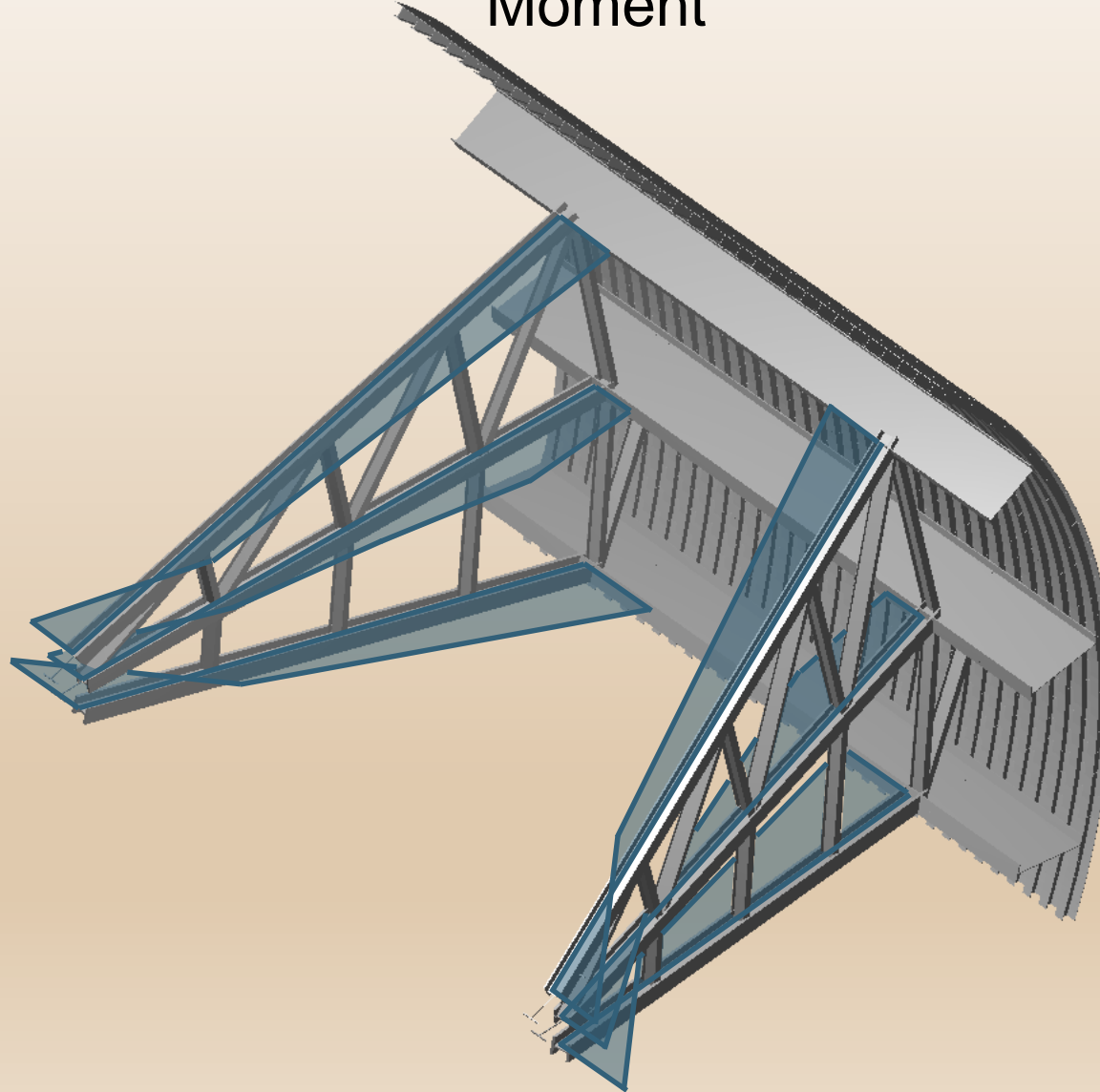
Load Effects

Strut Strong Axis
Moment



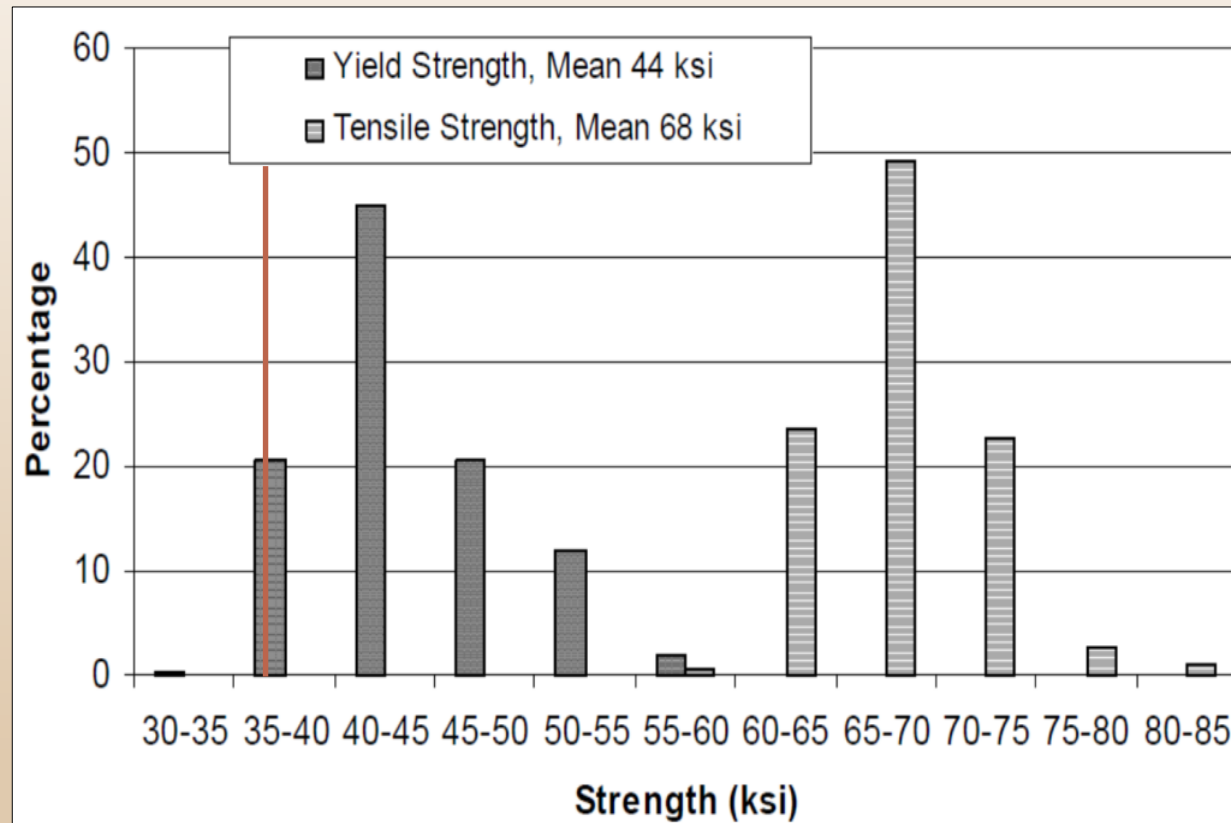
Load Effects

Strut Strong Axis
Moment



Capacity

Minimum Specified
Strength = 36 ksi



FEMA 355A

Limit State

Combined Flexure and Compression

$$IR = \begin{cases} \frac{P_r}{P_c} + \frac{8}{9} \left(\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}} \right) & \frac{P_r}{P_c} \geq 0.2 \\ \frac{P_r}{2P_c} + \left(\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}} \right) & \frac{P_r}{P_c} < 0.2 \end{cases}$$

Moment and axial demand should be calculated without load factors since uncertainty in loading is considered directly.

Moment and axial capacity should be calculated without resistance factors since uncertainty in material properties and resistance to buckling is considered directly.

Limit State

Combined Flexure and Compression

$$IR = \begin{cases} \frac{P_r}{P_c} + \frac{8}{9} \left(\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}} \right) & \frac{P_r}{P_c} \geq 0.2 \\ \frac{P_r}{2P_c} + \left(\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}} \right) & \frac{P_r}{P_c} < 0.2 \end{cases}$$

Weak axis moment generally has minimal impact at controlling load cases

Axial Load will dominate IR

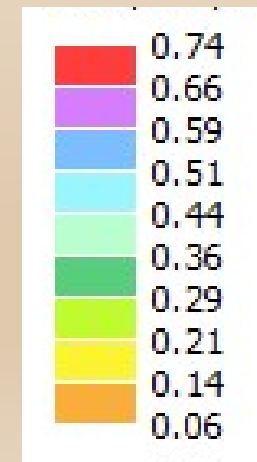
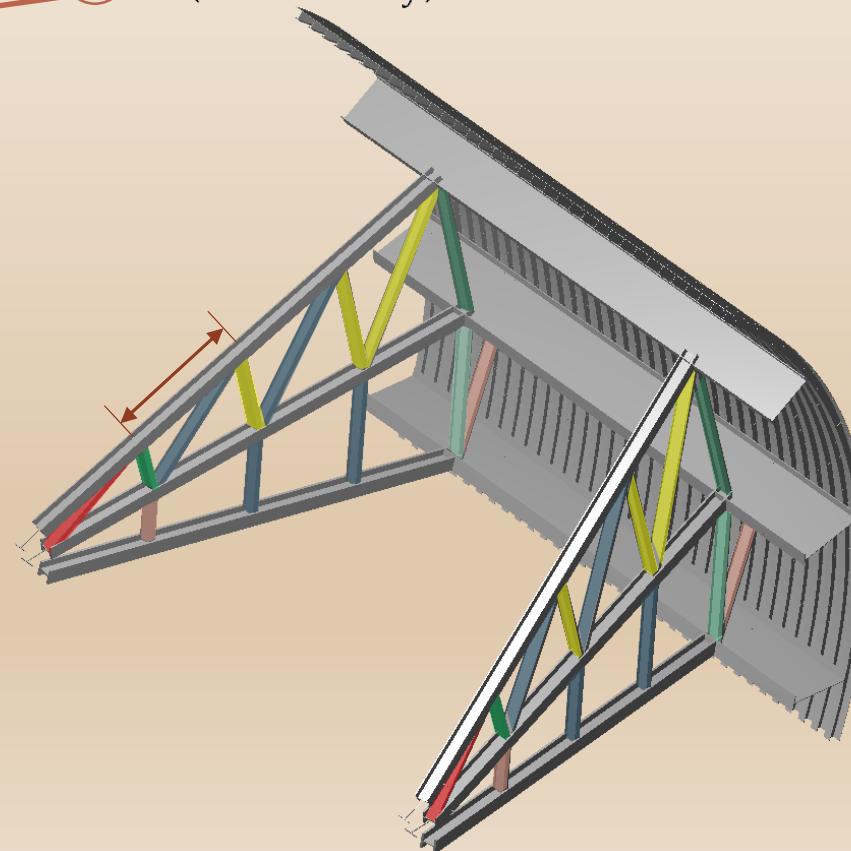
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What effective length should be used?

For buckling analysis, second order effects should also be considered.



Limit State

Combined Flexure and Compression

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What interaction ratio indicates failure?
Typically a fragility curve with increasing probability of buckling with increased IR should be used.

Interaction Ratio	Probability of Failure (1 gate)
< 0.5	0.0001
0.5 to 0.6	0.0001 to 0.001
0.6 to 0.7	0.001 to 0.01
0.7 to 0.8	0.01 to 0.1
0.8 to 0.9	0.1 to 0.9
0.9 to 1.0	0.9 to 0.99
> 1.0	0.9 to 0.999

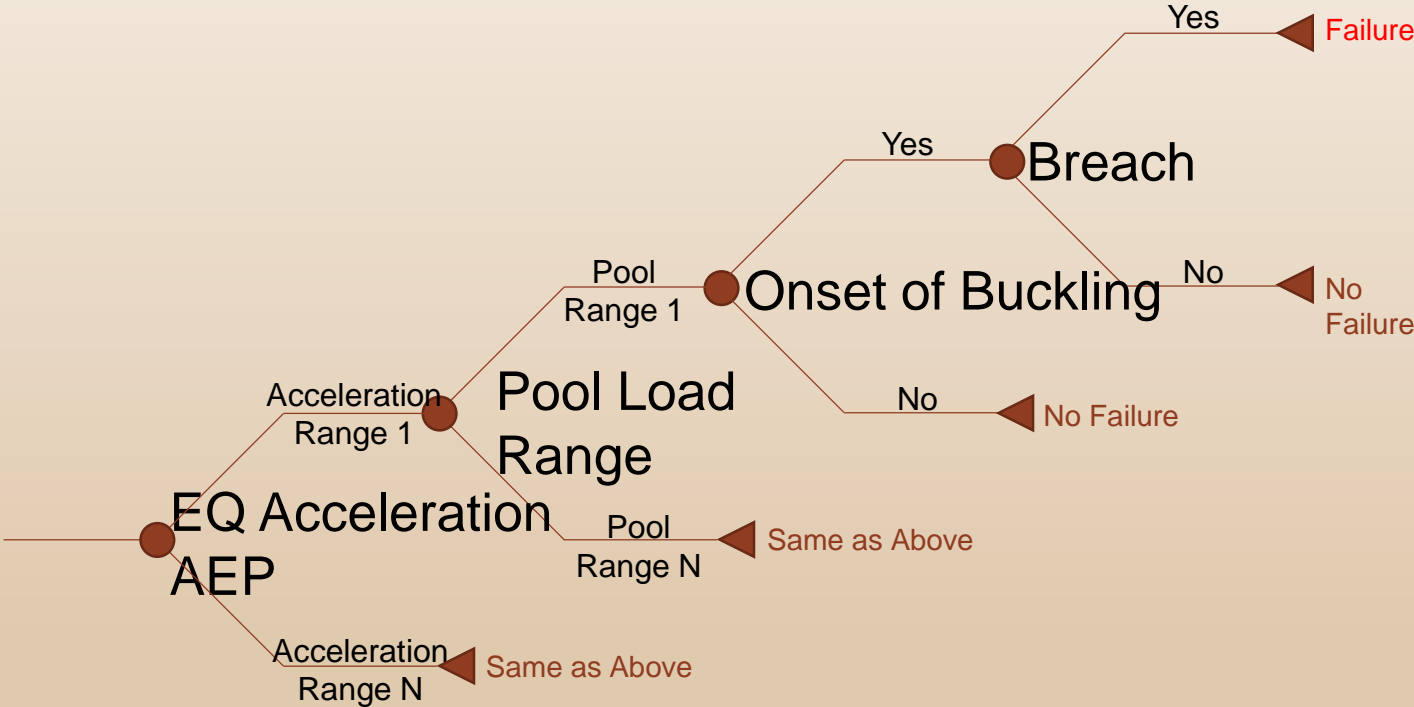
Fragility Curve for Seismic Gate Loading

- The same fragility curve as that used for normal operating conditions is recommended as a starting point
- This curve will be conservative for the dynamic component of the loading since buckling will be less likely for short duration loading
- The amount of change is difficult to predict and will likely be affected by the magnitude of the hydrodynamic loading component and the characteristics of the ground motions
- Risk teams can develop their own fragility curves to account for a reduced chance of buckling from hydrodynamic loads but should document the basis of the fragility curve
- A higher level analysis should be considered to better capture the response of the gates to seismic loading if a simpler approach is inconclusive



Example Results

PGA \ Pool	1585	1590	1595	1600
0.17	1.16E-09	2.50E-7	4.67E-4	0.016
0.3	1.00E-4	7.37E-3	0.106	0.505
0.5	7.98E-2	0.474	0.934	0.995
0.6	0.322	0.868	0.993	0.999



Finite Element Analysis

Various levels of finite element analysis can be used to better understand the behavior of the gates

- Uncoupled Pseudo-static: Essentially the same analysis as simplified hand calculations, but with the gate modelled in three dimensions and including all members.
- Uncoupled Response Spectrum: Three dimensional model of the gate with added mass to represent hydrodynamic pressures. Added mass should be oriented such that it is excited by motion perpendicular to the skin plate.
- Coupled Modal Time History: The spillway, gates, and piers are all modelled with added mass applied to represent hydrodynamic pressures. This will capture the interaction of the components, fully accounting for the amplification of the dam and any induced stresses from pier deflections.
- Coupled Direct Integration Time History: The full spillway structure is modelled as well as the water to fully consider the interaction of the gates with the water. Non-linear methods can also be incorporated if needed by using direct integration.



Gate Condition

- Many of our Tainter gates are 50+ years old and are starting to age.
- Navigation structures are particularly prone to corrosion and fatigue damage.
- Analysis should account for:
 - Known section loss
 - Known fatigue cracking
 - Potentially locked in moment from trunnion friction



Multiple Gates

$$P_f(k, N) = \binom{N}{k} p_f^k (1 - p_f)^{N-k} = \text{Probability that } k \text{ gates will fail out of a total of } N \text{ gates with independent and equal probability of failure, } p_f$$

$p_f^k (1 - p_f)^{N-k}$ = Probability that k gates will fail AND the $N-k$ gates DO NOT fail

$\binom{N}{k}$ = Number of ways to select k gates out of a total of N gates (“ N choose k ”)

Known as the binomial coefficient and can be determined using Pascal’s Triangle or

$$\binom{N}{k} = \frac{N!}{(N - k)! k!}$$

Generally assume gates are independent. If gate dependence is thought to be significant, use event tree method in Best Practices Manual or develop a method considering gate correlation.

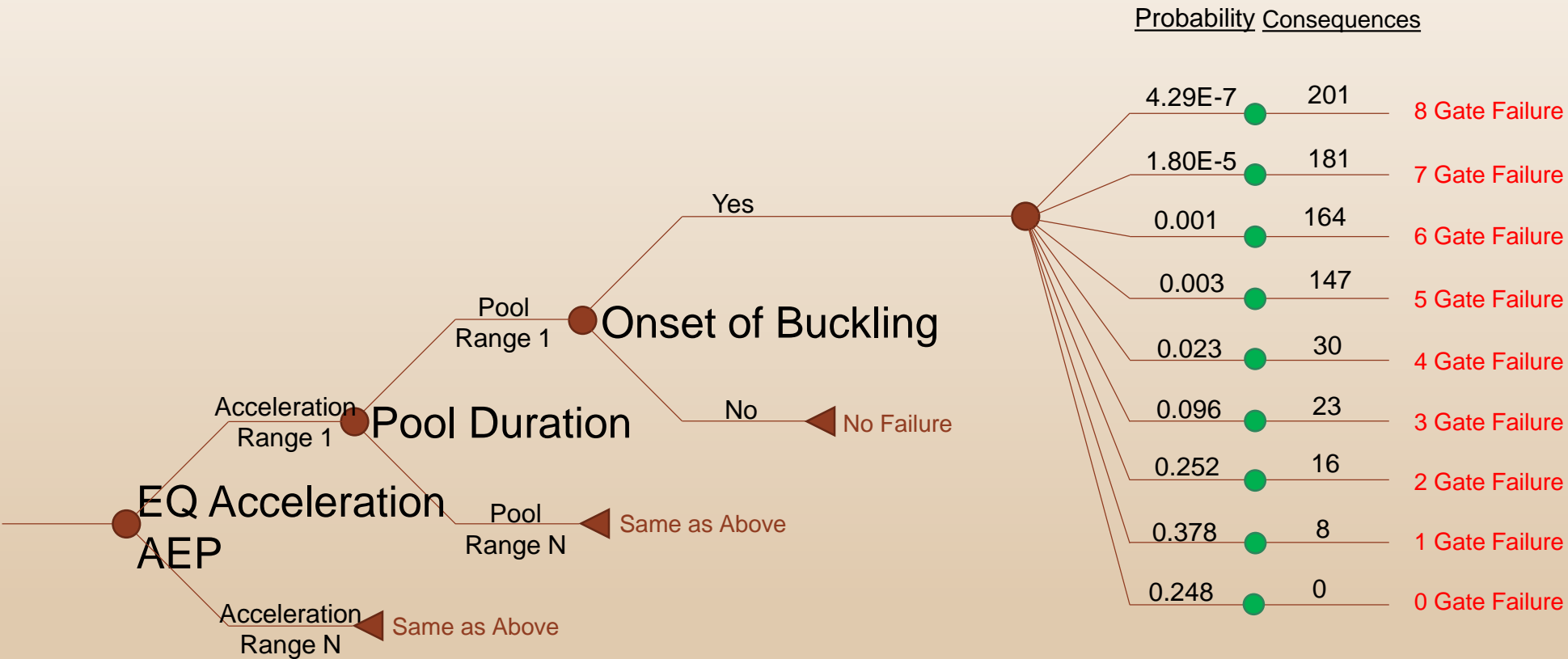


Multiple Gates

Number of Gates Failing	Probability of Failure Equations	Probability (P_x) of (x) Gates Failing	Expected Value Loss of Life	Loss of Life for (x) Gates Failing x (P_x)
1	$P_1 = 8(P)^1(1-P)^7$	0.378	8	3.022
2	$P_2 = 28(P)^2(1-P)^6$	0.252	16	4.029
3	$P_3 = 56(P)^3(1-P)^5$	0.096	23	2.206
4	$P_4 = 70(P)^4(1-P)^4$	0.023	30	0.685
5	$P_5 = 56(P)^5(1-P)^3$	0.003	147	0.512
6	$P_6 = 28(P)^6(1-P)^2$	0.001	164	0.054
7	$P_7 = 8(P)^7(1-P)^1$	1.80E-05	181	0.003
8	$P_8 = 1(P)^8(1-P)^0$	4.29E-07	201	8.63E-05
Totals		0.752	Weighted ave = 14 people	10.512



Multiple Gates



Multiple Gates and Additional Failure Modes

- Additional spillway failure modes such as trunnion pin, trunnion anchorage, and pier failure should also be considered.
- All of these failure modes lead to the same breach, so the probabilities must be combined without double counting.
- Combining the various failure modes and gates including correlations becomes too cumbersome to do mathematically with more than two gates.
- Even the most complicated problems can be solved easily through simulation.

Summary and Conclusions

- Simplified methods can be used to quickly develop probability of strut arm buckling estimates and perform sensitivity analysis
- To fully capture response of gate, finite element model is required
- To fully capture loading, coupled analysis is required.
- Gate condition and multiple gate bay breaches should be considered.

